Geologic Framework of the Ozarks of South-Central Missouri—Contributions to a Conceptual Model of Karst

By Randall C. Orndorff[1], David J. Weary[1], and Stanka Sebela[2]
[1]U.S. Geological Survey, MS926A National Center, Reston, VA 20192
[2]Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia

Abstract

A geologic framework is required to understand the environmental impact of proposed mining of lead and zinc on large springs in the karst area of south-central Missouri. Information about lithologies, faults, joints, and karst features (sinkholes, caves, and springs) contributes to the development of a conceptual model of karst hydrogeology. Conduits and caves along bedding planes and joints provide avenues for ground-water recharge, movement, and discharge. The trend of joints was studied to determine if they controlled the orientation of cave passages and conduits. The data show that cave passages are curvilinear and do no correlate well with measured joint trends. Instead, stratigraphy, bedding-plane dip, and local base level affect conduit and cave development. The majority of caves in south-central Missouri have developed within stromatolitic dolomite horizons beneath sandstone beds. It is thought that the sandstone beds act as confining units allowing artesian conditions and mixing to occur beneath them, thus, enhancing dissolution. Joints and the high primary porosity of the stromatolitic dolomite beds form openings in the bedrock that initiate solution. Where a solution-widened joint intersects a bedding plane, lateral movement of ground water is controlled by the bedding plane.

INTRODUCTION

Within bedrock regional aquifer systems in karst, the geologic framework provides critical information on the geologic boundary conditions. This paper presents results and observations related to the karst system of south-central Missouri acquired by geologic mapping, fracture analysis, cave and conduit mapping, and other related studies in and around the Ozark National Scenic Riverways, south-central Missouri. These observations and results provide the basis for a conceptual model of this complex karst system.

Geologic mapping at scales of 1:24,000 and 1:100,000 is being done in a part of the Ozark Plateaus in south-central Missouri, USA, to understand karst hydrology, especially relating to water quality and land-use issues on public lands. The study area is located in the Current River and Eleven Point River drainage basins and includes parts of the Ozark and Eleven Point National Scenic Riverways, the Mark Twain National Forest, several state forests, and some private lands (fig. 1). This area is characterized by many large springs, losing and disappearing streams, caves, and sinkholes. The terrain consists of steep-sided rolling hills and valleys, and entrenched, meandering streams; altitudes range from 135 to 400 m and the average relief is 120 to 150 m. The rocks in the study area are Upper Cambrian and Lower Ordovician dolomite,

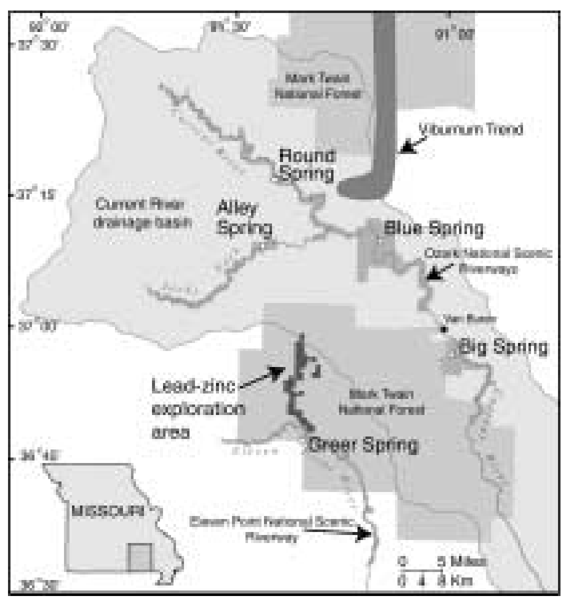

Figure 1. Index map of south-central Missouri showing Federal lands, mineral exploration area, large springs, and major rivers.

In Eve L. Kuniansky, editor, 2001, U.S. Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report 01-4011, p. 18-24

sandstone, limestone, shale, and chert, which overlie Middle Proterozoic rhyolite and granite.

The world's largest lead-zinc mining district, the Viburnum Trend, lies on the northern fringe of the study area. Exploration for similar deposits has been carried out in the Mark Twain National Forest near Greer Spring (fig. 1). Applications for permits to conduct mineral exploration in public lands have been requested by private industry in the past few years. Federal and State agencies are concerned about the environmental impact of exploration and potential mining activities on natural and recreational resources. These competing interests have generated a need for detailed geologic and hydrogeologic studies in order to provide data for informed land-management decisions. Geologic studies that identify karst, stratigraphy, and structural features contribute to the understanding of how ground water is transported.

GEOLOGIC AND HYDROGEOLOGIC SETTING

About 750 to 900 m of gently dipping Upper Cambrian and Lower Ordovician dolomite, sandstone, limestone, shale, and chert unconformably overlie Middle Proterozoic rhyolite and granite (fig. 2). Dolomite is the dominant rock type. Of the Upper Cambrian and Lower Ordovician rocks, only the Potosi Dolomite and younger units are exposed in the study area. Middle Proterozoic basement rocks are exposed as knobs that protrude into the Paleozoic section as high as the Gasconade Dolomite. Caves investigated for this study occur in the Eminence and Gasconade Dolomites, and the Roubidoux Formation. The Eminence Dolomite is a massive to thick-bedded, medium- to coarse-grained, light-gray, locally cherty dolomite with an intercalated sandstone bed in the eastern part of the study area. The Gasconade Dolomite contains a basal interbedded sandstone and dolomite unit, the Gunter Sandstone Member, overlain by medium- to thick-bedded, fine- to coarse-grained, light-gray dolomite with several cherty horizons. The Roubidoux Formation is interbedded fine- to coarse-grained, poorly sorted sandstone, thin- to medium-bedded, fine- to medium-grained dolomite, and chert. All three formations contain stromatolitic dolomite.

The Ozark Plateaus Province is a large structural dome. In southeastern Missouri, strata generally dip gently to the southeast toward the Mississippi embayment. Locally, strata dip steeply

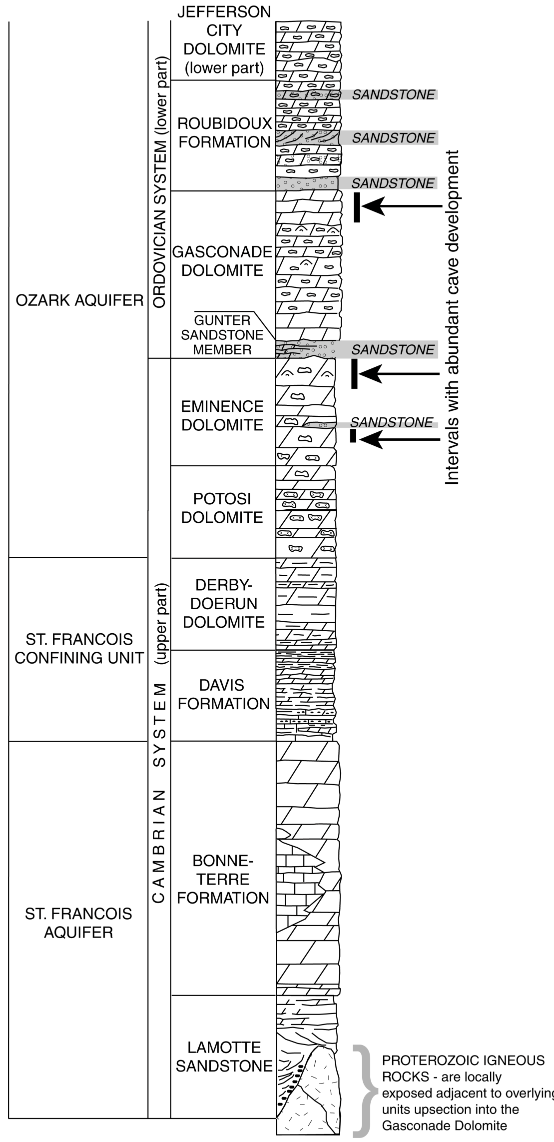

Figure 2. Stratigraphic and hydrogeologic units of south-central Missouri showing stratigraphic intervals with abundant cave development and highlighting sandstone horizons.

away from Middle Proterozoic knobs and near fault zones. Faults are generally steep and most have a northwest or northeast trend (fig. 3). Many faults in the Paleozoic rocks are aligned with Middle Proterozoic basement faults indicating that these faults may be reactivated. Faults with probable strike-slip motion have been identified in the study area by stratigraphic offset and the occurrence of fault breccia (McDowell, 1998; McDowell and Harrison, 2000; Orndorff and others, 1999; Weems, in press). Vertical joints in the Upper Cambrian and Lower Ordovician rocks occur in two dominant sets, 340^o-0^o and 70^o-90^o. The general trends of faults do not parallel these regional joint sets.

Upper Cambrian and Lower Ordovician strata form three geohydrologic units; two aquifers separated by a confining unit (Imes, 1990) (fig. 2). The lower aquifer, the St. Francois, is 30 to 180 m thick and consists of the Lamotte Sandstone and Bonneterre Formation. Overlying the St. Francois aquifer is the St. Francois confining unit (90-110 m thick) formed by shale, dolomite, and limestone of the Davis Formation and Derby-Doerun Dolomite. The upper aquifer, the Ozark (as much as 300 m thick), consists of the Potosi, Eminence, and Gasconade Dolomites, the Roubidoux Formation, and the Jefferson City Dolomite. The Ozark aquifer is the primary source for springs and streams and is used for domestic water supply.

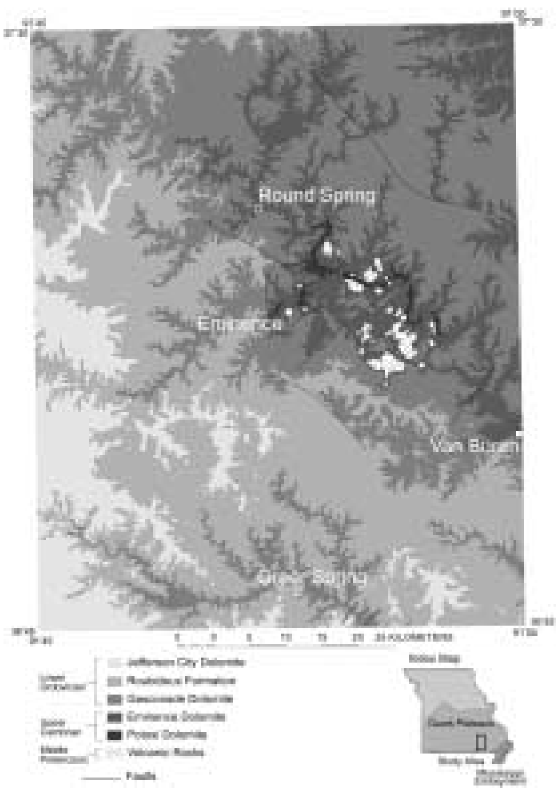

Figure 3. Generalized geologic map of south-central Missouri.

Distinctive karst features including underground drainage are abundant. Some of the largest springs in the United States are found in the area, including the two largest springs in Missouri, Big Spring (average flow 12 m^3/sec or 282 million gallons per day) and Greer Spring (8 m^3/sec or 183 million gallons per day) (fig. 1) (Vineyard and Feder, 1982). The discharge of all Ozark springs fluctuates with amount of precipitation. The prevalence of underground drainage is indicated by losing and disappearing streams as well as extensive cave and conduit systems. Dye traces show that subsurface drainage crosses surface drainage divides (Aley and Aley, 1987). For example, dye introduced in the Eleven Point River drainage basin surfaced at Big Spring along the Current River (Aley, 1975).

GEOLOGY OF THE CAVE AND CONDUIT SYSTEM

Thirty nine caves were visited and studied in order to understand the geologic controls on the development of the Ozark cave and conduit system. Geologic mapping of 19 of these cave systems included stratigraphy, passage orientations, fracture measurements, and passage morphology. In addition, 42 maps of other caves in the study area were examined for passage orientations and morphology. Sebela and others (1999) discuss the geology of four caves in detail, including stratigraphy, structure, hydrology, and cave development. For this paper, a cave is defined as a natural underground opening large enough for a human to enter; a conduit is smaller in size.

The Role of Joints in Cave and Conduit Development

To determine the role of joints in cave and conduit development, orientations of cave passages were compared to regional and local joint trends. This was done in two ways: first, by comparing passage orientations with joints measured in several caves, and second, by comparing the passage orientations of all of the caves in the study area to the regional joint trends. In this area of the Ozarks, joints in the Cambrian and Ordovician rocks are vertical to subvertical and have a bimodal distribution (fig. 4a).

A detailed study of four caves showed that although there were some passage orientations parallel to joints measured in the caves (fig. 5c and 5d), the passages are branching and meandering and have scattered orientations (fig. 5) (Sebela and others, 1999). Cave passage orientations of 58 caves (14,260 m of passage) in the study area were compared to joint trends measured during bedrock geologic mapping on the surface (fig. 4). Joint trends in Cambrian and Ordovician dolomite are bimodal with the trends of 340°-0° and 70°-90°. Compass-rose diagrams of cave passage orientations overall show much variation (fig. 4b). It is apparent that there is no correlation between joint orientations and trends of cave passages.

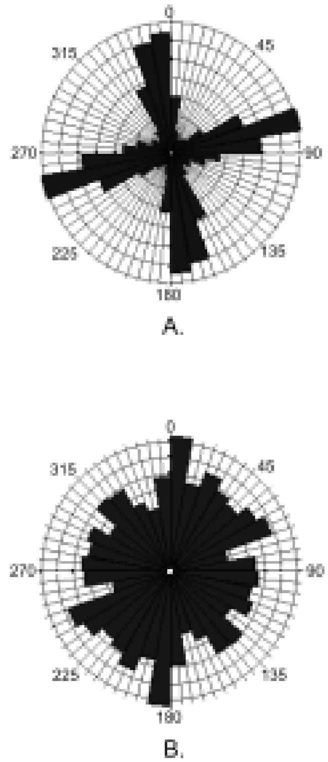

Figure 4. Compass-rose diagrams showing (A) orientation of joints measured in the study area, n=5,285, each circle represents 2 percent of total, maximum 14 percent, and (B) orientation of cave passages, n=14,260 m, each circle represents 1 percent of total, maximum 8 percent.

The Role of Bedding in Cave and Conduit Development

Evidence for bedding control on cave and conduit development in the Ozarks includes a relationship between cave horizons and stratigraphic position, the branching morphologies of the caves, caves parallel or subparallel to bedding horizons, and the lack of correlation between cave passages and joint trends. As discussed previously, joint trends do not correlate with cave passage trends suggesting other geologic controls on the development of the cave and conduit system. Palmer (1991) showed that branching cave systems are indicative of bedding control where curvilinear passages of branchwork morphology are controlled by bedding parting porosity.

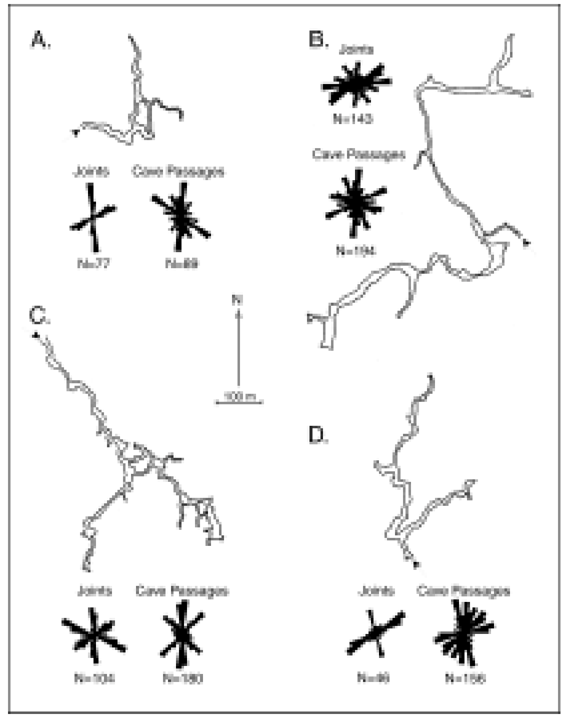

Figure 5. Cave plans and compass-rose diagrams of joints in caves and cave passages for (A) Branson Cave, (B) Round Spring Cavern, (C) Wind Cave, and (D) New Liberty Cave. Cave plans reduced from maps produced by the Cave Research Foundation. Arrows indicate cave entrances. Cave passages were weighted with respect to length.

Cave horizons almost exclusively occur immediately below sandstone horizons in the stratigraphic section (fig. 2). Sandstone horizons occur within the Eminence Dolomite in the eastern part of the study area, at the base of the Gasconade Dolomite as the Gunter Sandstone Member, and at the base and within the Roubidoux Formation. Ninety-four percent of all caves examined in this study are directly below sandstone. The sandstone within the Eminence Dolomite pinches out in the western part of the study area, and where it does not exist, the correlative dolomite horizon does not contain caves. Although it is difficult to determine the role of the sandstone in the development of caves, its role as a confining unit is evident because in this region it has a relatively low primary porosity. Several possibilities for dissolution below sandstone include a change in the chemistry of water as it migrates through fractures within the sandstone, concentrated recharge beneath the sandstone cap (Palmer, 2000), or aggressive water due to increased pressure and mixing below the confining sandstone horizons (artesian conditions). Arakaki and Mucci (1995) showed that increasing the partial pressure of CO_2 decreases the pH of the solution. In confining conditions beneath the sandstone, this drop in pH can make the ground water more aggressive and therefore enhance dissolution within these horizons. Also, Shi and Zhang (1992) modeled dissolution in confining conditions in gently dipping strata and found that caves developed near the top of the confined aquifer. It is possible that the sandstone was a confining unit in the past and the increased pressure on the system contributed to solution in the dolomite beneath the sandstone (fig. 6). Since ground water in confined conditions would have to travel long distances and are not close to recharge areas, epigenic water sources dependent on soil CO_2 are limited (Klimchouk, 2000).

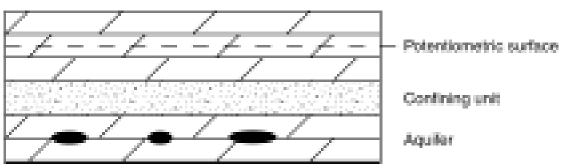

Figure 6. Diagrammatic cross section showing sandstone as a confining layer and the potentiometric surface above the confining unit. Black ovals represent caves. Water in the aquifer is under pressure and enhances dissolution because of decrease in pH.

Deep-seated sources of aggressive water in the Ozarks include organics in the stratigraphic section and sulfates from mineralization in this area. Palmer (2000) noted that interaction between sulfates and carbonates greatly increases the solubility of dolomite. The upper part of the aquifer under pressure would be a likely place for enhanced dissolution from the mixing of meteoric water with the deep-seated waters. It is generally accepted that solutional aggressiveness can be enhanced by mixing water of differing chemistry (Klimchouk, 2000). The branchwork type of cave morphology is also consistent with cave development under confining conditions (Palmer, 1991; 2000). Ford and others (2000) showed that increasing pressure gradients allow fluid to travel greater distances before attaining saturation and create a larger incidence of branching channels.

Most cave horizons occur in stromatolitic dolomite. Vugs in stromatolitic dolomite have a higher primary porosity than other dolomite horizons. Since stromatolitic dolomite occurs throughout the stratigraphic section and not just beneath sandstone horizons, it is presumed that the sandstone plays a more important role in the development of the cave and conduit system. The vugs within the dolomite provide the surface area for dissolution to occur.

Although most cave passages have been modified in the vadose zone by cave streams (canyon cutting) and ceiling breakdown, some still show their phreatic origin as tubes. These cave segments show how bedding plane partings are the control on development as joints are not seen in many of the passages (fig. 7). These bedding plane partings may be open from gentle folding allowing for dissolution to occur along them.

Figure 7. Photograph of passage in Camp Yarn Cave. Note phreatic tube-like morphology and lack of joints in ceiling. Phreatic tube developed along a bedding plane parting.

CONCEPTUAL MODEL

Figure 8 is a diagram of the karst hydrologic system for the Ozarks of south-central Missouri. Precipitation that does not evaporate or runoff into surface streams enters the karst system through diffuse infiltration and sinkholes. Some component of ground water also enters from losing streams. In the Ozark aquifer, the cave and conduit system along with fractures in the vadose zone transports water both laterally to springs and seepage areas and vertically to the water table. Active dissolution occurs near the top of the phreatic zone where carbonic acid in meteoric waters reacts with the carbonate rock. Ground water from the phreatic conduits is then discharged to the Current River and Jacks Fork through large springs such as Big Spring, Greer Spring, Blue Spring, Alley Spring, and Round Spring (fig. 1). Dissolution may also be occurring near the top of the confined St. Francois aquifer by methods described above. Active dissolution in the St. Francois aquifer would require a source of aggressive water produced by mixing near the top of the aquifer. Most water in this aquifer is stored in the fracture and pore system.

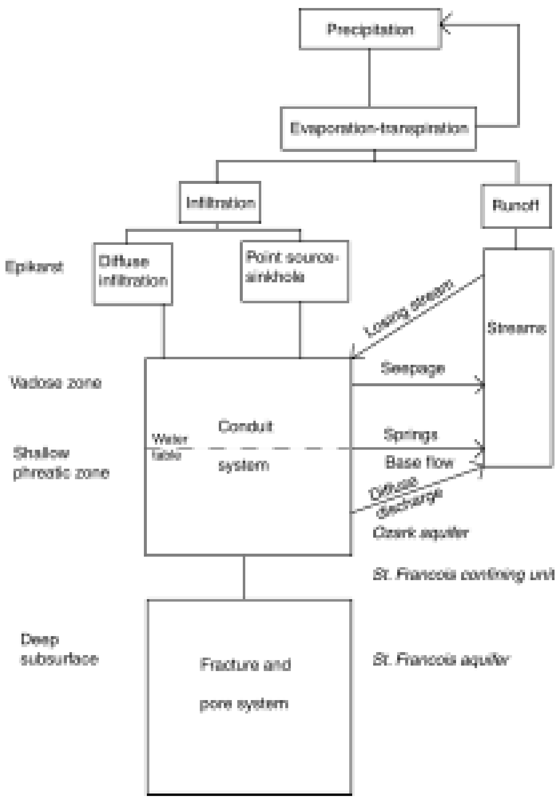

Figure 8. Diagram showing the karst hydrologic system of the Ozarks of south-central Missouri.

CONCLUSIONS

The dominant geologic controls on cave and conduit development in the Ozarks of south-central Missouri are bedding and stratigraphy. Primary porosity as vugs in the stromatolitic dolomite and secondary porosity as joints are the pre-solutional openings where dissolution is initiated. After a certain conduit width is achieved, bedding planes then control the lateral movement of ground water. These bedding planes are more readily used for ground-water movement than joints because they are more continuous. Preferential horizons for cave and conduit development are beneath sandstones. These sandstones are hypothesized to act as confining units where hydraulic pressure beneath them and mixing of water with differing chemistry increases dissolution in the dolomite beds underlying them.

By understanding these geologic controls on karst development along with hydrogeologic properties of aquifers, land-use managers can have a better understanding of the water resources in this area of potential lead and zinc mineralization. The dip of bedding planes as part of subtle structures, as delimited on geologic maps, may help to understand the direction of ground-water flow. This would then help to determine if mining activities in the National Forest in certain areas would environmentally effect the ground-water and spring system in the Ozark National Scenic Riverways.

ACKNOWLEDGEMENTS

The authors thank Robert Osburn, Scott House, and Mick Sutton of the Cave Research Foundation for caving support and access to cave maps. Also, the authors thank the Ozark National Scenic Riverways and Mark Twain National Forest for access to various caves. This paper was improved by the thoughtful and constructive reviews of Jack Epstein and Thomas Armstrong.

REFERENCES

Aley, T.J., 1975, A predictive model for evaluating the effects of land use and management on the quantity and quality of water from Ozarks springs: U.S. Forest Service Speleology 18, p. 1-185.

Aley, T.J., and Aley, C., 1987, Groundwater study—Ozarks National Scenic Riverways: Protem, MO, Ozark Underground Laboratory, National Park Service Contract CX 6000-4-0083, 222 p.

Arakaki, Takeshi, and Mucci, Alfonso, 1995, A continuous and mechanistic representation of calcite reaction-controlled kinetics in dilute solutions at 25°C and 1 Atm total pressure: Aquatic Geochemistry, v. 1, p. 105-130.

Ford, Derek, Lauritzen, S., and Ewers, Ralph, 2000, Hardware and software modeling of initial conduit development in karst rocks, *in*, Klimchouk, A.B., Ford, D.C., Palmer, A.N., Dreyboldt, Wolfgang, eds., Speleogenesis—evolution of karst aquifers: Huntsville, AL, National Speleological Society, p. 175-183.

Imes, J.L., 1990, Major geohydrologic units in and adjacent to the Ozarks Plateaus Province, Missouri, Arkansas, Kansas, and Oklahoma—Ozark aquifer: U.S. Geological Survey Hydrologic Atlas HA-711-E, 3 sheets, scale 1:750,000.

Klimchouk, Alexander, 2000, Speleogenesis under deep-seated and confined settings, *in*, Klimchouk, A.B., Ford, D.C., Palmer, A.N., Dreyboldt, Wolfgang, eds., Speleogenesis—evolution of karst aquifers: Huntsville, AL, National Speleological Society, p. 244-260.

McDowell, R.C., 1998, Geologic map of the Greer quadrangle, Oregon County, Missouri: U.S. Geological Survey Geologic Investigations Map I-2618, scale 1:24,000.

McDowell, R.C., and Harrison, R.W., 2000, Geologic map of the Powder Mill Ferry quadrangle, Shannon and Reynolds Counties, Missouri: U.S. Geological Survey Geologic Investigations Map I-2722, scale 1:24,000.

Orndorff, R.C., Harrison, R.W., and Weary, D.J., 1999, Geologic map of the Eminence quadrangle, Shannon County, Missouri: U.S. Geological Survey Geologic Investigations Map I-2653, scale 1:24,000.

Palmer, A.N., 1991, Origin and morphology of limestone caves: Geological Society of America Bulletin, v. 103, p. 1-21.

Palmer, A.N., 2000, Hydrogeologic control of cave patterns, *in*, Klimchouk, A.B., Ford, D.C., Palmer, A.N., Dreyboldt, Wolfgang, eds., Speleogenesis—evolution of karst aquifers: Huntsville, AL, National Speleological Society, p. 77-90.

Sebela, Stanka, Orndorff, R.C., and Weary, D.J., 1999, Geological controls in the development of caves in the south-central Ozarks of Missouri, USA: Acta Carsologica, v. 28/2, p. 273-291.

Shi Mengxiong and Zhang Shouyue, 1992, Simulation test of model for development of cave system in gently dipping-rocks: Scientia Geologica Sinica, v. 3, p. 298-304.

Vineyard, J.D., and Feder, G.L., 1982, Springs of Missouri: Missouri Geological Survey and Water Resources, Water Resources Report 29, 212 p.

Weems, R.E., in press, Geologic map of the Low Wassie quadrangle, Oregon and Shannon Counties, Missouri: U.S. Geological Survey Geologic Investigations Map I-2719, scale 1:24,000.